Agriculture – Crop yields, soil erosion, and soil carbon

Statement of the Problem

Rising atmospheric CO_2 concentrations and global climate change could potentially have significant effects on American agriculture. While elevated CO_2 may have a beneficial effect on crop growth, increased temperature and changes in precipitation, wind, and other climatic variables may alter crop yields. These climatic changes may also affect rates of soil erosion and the carbon content of agricultural soils, which may affect carbon sequestration.

Soils are a major reservoir of global carbon, and are equal in magnitude to the combined global carbon content of the entire atmosphere plus all aboveground biomass. Loss of agricultural soil carbon through erosion, management, and decomposition adds to the atmospheric loading of CO_2. Agricultural management practices which conserve or sequester soil carbon can help mitigate the rate of increase of atmospheric CO_2. Assessments of the potential for such mitigation through widespread adoption of best management practices for major American agricultural areas are needed as well.

Approach

Research focused on model assessments of the sensitivity of soil erosion to precipitation change scenarios across the US, and more detailed evaluations of crop yield, soil erosion, and soil carbon responses to climate change scenarios including temperature, precipitation, wind, and CO_2 in the US Corn Belt. The research focused on two erosional processes: (1) water erosion which is the loss of soil due to rainfall runoff from field crops, and (2) wind erosion which is the loss of soil due to wind blown particles. Assessments were also made of the effects of widespread adoption of various management practices on soil erosion and soil carbon in the United States to mitigate the rate of atmospheric CO_2 increase. Management scenarios included the current mix of tillage and crop rotation practices, and increased use of crop rotation and conservation tillage practices which have become more prevalent in recent years.

Main Conclusions

Projected water erosion of soil for U.S. croplands, pasturelands, and rangelands increased with increases in precipitation in the $2xCO_2$ climate change scenarios from four atmospheric General Circulation Models (Phillips *et al.* 1993b). Changes in erosion were greater when precipitation changes were assumed to be from changes in storm intensity rather than storm frequency, indicating the importance of the manner in which climatic changes occur in addition to their mean magnitude. Recent reductions in national soil erosion indicate the potential for management changes to mitigate the magnitude of erosion increases projected under these climate change scenarios.

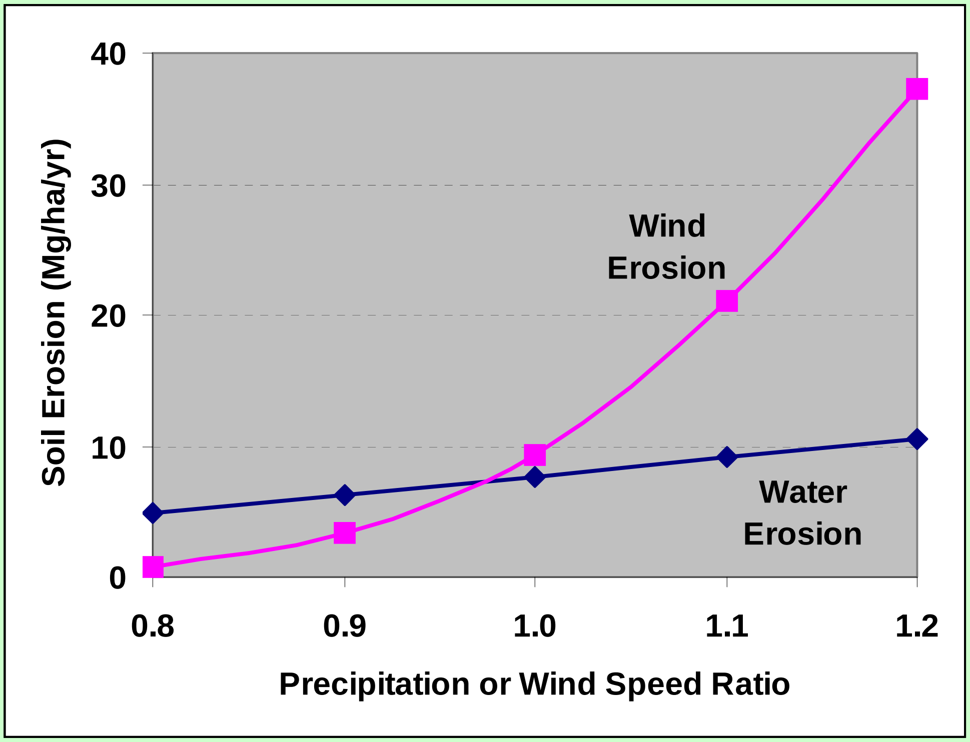
In a detailed model assessment using 36 climate/CO_2 scenarios for croplands in the U.S. Corn Belt, water erosion linearly tracked increasing or decreasing precipitation, but wind erosion showed dramatic increases as mean wind speeds increased (Lee *et al*. 1996). Increasing temperature alone decreased water erosion while increasing wind erosion and total erosion (water and wind). But, beneficial effects of elevated CO_2 on plant growth nullified this effect on total soil erosion.

Typical of agricultural soils under long-term cultivation, soil carbon decreased over the 100 year simulations, adding to atmospheric CO_2 loadings. This carbon loss was accelerated by increased temperature and precipitation, but elevated CO_2 slowed the loss rate. Corn and soybean crop yields were projected to decrease slightly due to temperature or wind increases alone, track precipitation increases or decreases, and increase markedly in response to an 80% increase in CO_2 (Phillips *et al*. 1996).

Model assessments of alternative management practices in the U.S. Corn Belt showed that increasing use of conservation tillage practices such as mulch-till and no-till could substantially reduce the loss of soil carbon due to erosion and decomposition (Phillips *et al.* 1993a, Lee *et al.* 1993). Agricultural soils could become a small sink for carbon with widespread use of no-till cultivation and use of a winter cover crop (Lee *et al*. 1993). This indicates the potential for changing agricultural management practices to mitigate the buildup of atmospheric CO_2 and associated climatic change. Conservation tillage is economically and functionally feasible and is likely to occur because of land and soil conservation benefits from conservation tillage and rising fuel costs (Kern and Johnson 1993).

Wind and water erosion

Sensitivity of Corn Belt soil erosion to climatic changes



This figure shows projected soil loss by water and wind erosion across croplands in the U.S. Corn Belt under an elevated atmospheric CO_2 concentration of 625 ppm and a temperature increase of 2^{o} C above current conditions. Current conditions for precipitation and wind speed are represented by a ratio of 1.0. When precipitation in the climate scenario is varied from 20% below current levels (ratio of 0.8) to 20% above current levels (ratio of 1.2), water erosion increases linearly. In contrast as mean wind speeds in the climate scenario are varied from –20% to +20% compared to current levels, there is a dramatic non-linear increase in wind erosion.

Carbon Sequestration in Soil

Soil organic matter is the largest global terrestrial carbon (C) pool and is a source of CO_2, CH_4, and other greenhouse gases. Soil management affects the amount of C held in soil and the greenhouse gas emissions from soil. In the agricultural sector conventional tillage practices such as the use of a moldboard plow, lead to a steady loss of soil C to the atmosphere. In contrast, conservation tillage practices that include minimum tillage and no-till conserve soil C and reduce that amount of fossil fuel needed for tillage.

Kern and Johnson (1993) conducted an analysis of the amount of soil C that would either be lost or sequestered and the amount of fossil fuel required for agriculture in the contiguous United States using three scenarios of conservation tillage: 27% (Scenario 1), 57% (Scenario 2) and 76% (Scenario 3). The analysis covered 30 years beginning in 1990. For Scenario 1, the level of conservation tillage was held constant at the actual 1990 level of 27% for 30 years. For Scenarios 2 and 3, both began at 27% in 1990 and linearly ramped up to 57% and 76%, respectively, over the first 20 years of the analysis and were held constant for the remaining 10 years.

Maintaining 1990 levels of conventional and conservation tillage resulted in a net loss of 41 Tg of soil C (1 Tg = 10^{12}g) over the 30-year period while using 157 Tg of fossil fuel. A combined 198 Tg of C was estimated to be added to the atmosphere under Scenario 1. For Scenario 2, a net sequestration of C in soil (+80 Tg) was achieved while fuel consumption dropped slightly. Fossil fuel consumption did not drop concomitantly because reduced tillage systems require more herbicides and pesticides -- derived from fossil fuels -- than conventional tillage systems. For Scenario 3, an additional 364 Tg of soil C sequestered and 146 Tg of fossil fuel consumed, for a net gain of 218 Tg of C.

Changes in soil organic C and fossil fuel C emission for three scenarios of conservation tillage (CT) for agriculture in the contiguous U.S. projected from 1990 to 2020.

	Scenarios of Conservation Tillage (CT)					
	27% CT[a]		57% CT[b]		76% CT[c]	
Tillage System	Soil	Fuel	Soil	Fuel	Soil	Fuel
Conventional Tillage	-41	-121	-24	-87	-13	-67
Minimum Tillage	0	-30	0	-52	0	-66
No-Tillage	0	-6	+104	-10	+377	-13
Sums	-41	-157	+80	-149	+364	-146
Net Loss (-) or Gains (+)	-198		-69		+218	

a) 27% CT scenario uses the level of conservation tillage used in 1990 (~27%) held constant for 30 years until 2020.
b) 57% CT scenario begins in 1990 with 27% conservation tillage and linearly ramps up to 57% conservation tillage over 20 years (2010) and remains constant at 57% until 2020.
c) 76% CT scenario begins in 1990 with 27% conservation tillage and linearly ramps up to 76% conservation tillage over 20 years (2010) and remains constant at 76% until 2020.

References Cited

Kern, J.S. and M.G. Johnson. 1993. Conservation Tillage Impacts on National Soil and Atmospheric Carbon Levels. Soil Science Society of America Journal 57:200-210.

Lee, J.J., D.L. Phillips, and R. Liu. 1993. The effect of trends in tillage practices on erosion and carbon content of soils in the U.S. Corn Belt. Water, Air, and Soil Pollution 70: 389-401.

Lee, J.J., D.L. Phillips, and R.F. Dodson. 1996. Sensitivity of the U.S. Corn Belt to climate change and elevated CO2: II. Soil erosion and organic carbon. Agricultural Systems 52: 503-521.

Phillips, D.L., P.D. Hardin, V.W. Benson, and J.V. Baglio. 1993a. Non-point source pollution impacts of alternative agricultural management practices in Illinois: a simulation study. Journal of Soil and Water Conservation 48: 449-457.

Phillips, D.L., D. White, and C.B. Johnson. 1993b. Implications of climate change scenarios for soil erosion potential in the United States. Land Degradation and Rehabilitation 4: 61-72.

Phillips, D.L., J.J. Lee, and R.F. Dodson. 1996. Sensitivity of the U.S. Corn Belt to climate change and elevated CO2: I. Corn and soybean yields. Agricultural Systems 52: 481-502.

Annotated Bibliography of WED Research

Johnson, Mark G. 1995. The role of soil management in sequestering soil carbon. *In* International Symposium on Soil Processes and Management Systems: Greenhouse Gas Emissions and Carbon Sequestration. Advances in Soil Science.

Soils are an important component of the global carbon cycle and serve as a large reservoir of terrestrial carbon. The amount of carbon in any soil is a function of the soil forming factors including: climate, relief, organisms, parent material, and time. Over the centuries, humans, usually included as part of the "organisms" factor, have profoundly influenced the dynamics and sequestration of carbon in soils by their land use and management practices. These practices include cultivation, deforestation, and draining wet soils. In general, human activities have decreased the amount of carbon held in affected soils. With the concern over increasing concentrations of greenhouse gases, humans need to consider how soil management affects greenhouse gas emissions from soil and the sequestration of carbon in soils, and to look for ways to protect and manage soil carbon. This paper examines soil management practices and their effects on greenhouse gas emissions and carbon sequestration. Included is an analysis of how management practices affect the physical and chemical environment of soil and how these in turn affect greenhouse gas emissions and the soil carbon sequestration potential.
support

Johnson, Mark G., Elissa R. Levine and Jeffrey S. Kern. 1995. Soil organic matter: distribution, genesis, and management to reduce greenhouse gas emissions. Water, Air and Soil Pollution 82:593-615.

In this paper we describe the accumulation of soil organic matter (SOM) during pedogenesis and the processes that can lead to the emission of greenhouse gases (CO_2, CH_4, N_20) to the atmosphere via SOM decomposition and denitrification. We discuss the role of management on SOM accumulation and loss, and the potential for controlling emission or consumption of greenhouse gases by soils. We conclude that under current climate conditions there are global scale opportunities to reduce greenhouse gas emissions from soils and increase the indirect sequestration of greenhouse gases in soils through improved soil management.

Kern, J.S. and M.G. Johnson. 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Science Society of America Journal 57:200-210.

Soil organic matter is the largest global terrestrial C pool and is a source of CO_2, CH_4, and other greenhouse gases. Changes in soil organic C (SOC) content and fossil fuel C emissions in response to conversion of conventional tillage to conservation tillage in the contiguous USA for field crop production by the year 2020 were projected by developing a model based on published data, and geographic databases of current conservation tillage usage and agricultural SOC. Three scenarios of conservation tillage use, 27% (current usage), 57% (Scenario 2), and 76% (Scenario 3) of field cropland planted, were considered. The SOC content for major field crops to 30-cm depth was 5304 to 8654 Tg C (Tg = 10^{12} g), with 1710 to 2831 Tg C at 0- to 8-cm depth, and 1383 to 2240 Tg C at 8- to 15-cm depth. Maintaining current levels of conventional tillage until 2020 would result in 31 to 52 Tg SOC loss. Scenario 2 conventional tillage resulted in 18 to 30 Tg C SOC loss, and Scenario 3 yielded 9 to 16 Tg SOC loss, which were C savings of 21 to 36 Tg C over maintaining current levels of tillage. Conversion of conventional tillage to no-till resulted in 80 to 129 Tg C gain in soil for Scenario 2, and 286 to 468 Tg C for Scenario 3. No-till and conventional tillage had similar SOC contents below the 15-cm depth. Minimum tillage conserved current levels of SOC but did not consistently increase SOC above levels of conventional tillage. Fossil fuel emissions from field manipulations and herbicide production for conventional tillage are 53 kg C ha^{-1} yr^{-1}, minimum tillage is 45 kg C ha^{-1} yr^{-1}, and 29 kg C ha^{-1} yr^{-1} for no-till. Fuel emissions for maintaining current levels of tillage practices are 157 Tg C, 149 Tg C for Scenario 2, and 146 Tg C for Scenario 3 for 30 yr. Increasing the amount of conservation tillage to Scenario 3 levels will change these agricultural systems from sources of C (188-209 Tg C) to C sinks (131-306 Tg C). The SOC benefit of Scenario 3 (277-452 Tg C) is equivalent to 0.7 to 1.1% of the total projected U.S. fossil fuel C emissions for the next 30 yr.

Lee, J.J., D.L. Phillips and V.W. Benson. 1999. Soil erosion and climate change: assessing potential impacts and adaptation practices. Journal of Soil and Water Conservation 54:529-536.

Changes in climate associated with changes in atmospheric concentrations of CO_2 and other greenhouse gases might affect soil erosion by wind and water. Changes in erosion could in turn cause changes in productivity and sustainability of agricultural systems, and changes in air quality (PM_{10}) and water quality (sediment transport). Substantial effects on productivity may, however, only occur several decades after climate changes. This paper preserves a procedure for assessing the potential effects of climate change on erosion and productivity. A preliminary screening process is used to identify and prioritize regions and management systems. Subsequent simulation of selected sites with the EPIC model is used to investigate potential practices to adapt agricultural systems to climate change. In some cases, proposed adaptation strategies might reduce sustainability if they are not matched to environmental conditions found at specific sites. As an example, the assessment procedure is applied to evaluate vulnerability and adaptation practices for a 20% increase in mean monthly wind speeds in the U.S. corn belt.

Lee, Jeffrey J., Donald L. Phillips and Rusty F. Dodson. 1996. Sensitivity of the US corn belt to climate change and elevated CO_2: II. Soil erosion and organic carbon. Agricultural Systems 52:503-521.

Climate models indicate that increasing atmospheric concentrations of carbon dioxide and other greenhouse gases could alter climate globally. The EPIC (Erosion/Productivity Impact Calculator) model was used to examine the sensitivity of soil erosion (wind, water) and soil organic carbon (SOC) (15 cm and 1 m depth) across the US corn belt to changes in temperature (+ 2°C), precipitation ($\pm$ 10%, $\pm$ 20%), wind speed ($\pm$ 10%, $\pm$ 20%), and atmospheric CO_2 concentration (350, 625 ppmv). One-hundred-year simulations were run for each of 100 sites under 36 climate/CO_2 regimes. The100-year regionally aggregated mean water erosion rates increased linearly with precipitation, whereas the wind erosion rates decreased and total erosion rates increased non-linearly. Increasing temperature by 2°C (with CO_2 and mean wind speed held constant) decreased water erosion by 3-5%, whereas wind erosion increased by 15-18%. Total erosion increased with increased temperature. Increasing CO_2 from 350 to 625 ppmv (with temperature increased by 2°C and mean wind speed held constant) had no effect on water erosion, despite increases in annual total and peak runoff; this was attributed to increased vegetation cover. Wind erosion decreased by 4-11% under increased CO_2. Wind erosion was very sensitive to mean wind speed, increasing four-fold and decreasing 10-fold for a 20% increase or decrease in mean wind speed, respectively. This was attributed to a threshold effect. SOC to 1 m decreased 4.8 Mg-C ha^{-1} from an initial value of 18.1 Mg-C ha^{-1} during the 100-year baseline simulation. About 50% of this loss (2.3 Mg-C ha^{-1}) was due to transport offsite by soil erosion. SOC in the top 15 cm decreased 0.8 Mg-C ha^{-1} from an initial value of 4.9 Mg-C ha^{-1}. Increased temperature and precipitation accelerated these losses of SOC, whereas increased CO_2 slowed the losses.

Lee, J.J., D.L. Phillips and R. Liu, 1993. The effect of trends in tillage practices on erosion and carbon content of soils in the US corn belt. Water, Air, and Soil Pollution 70:389-401.

The EPIC model was used to simulate soil erosion and soil C content at 100 randomly selected sites in the US corn belt. Four management scenarios were run for 100 years: (1) current mix of tillage practices maintained; (2) current trend of conversion to mulch-till and no-till maintained; (3) trend to increased no-till; (4) trend to increased no-till with addition of winter wheat cover crop. As expected, the three alternative scenarios resulted in substantial decreases in soil erosion compared to the current mix of tillage practices. C content of the top 15 cm of soil increased for the alternative scenarios, while remaining approximately constant for the current tillage mix. However, total soil C to a depth of 1 m from the original surface decreased for all scenarios except for the no-till plus winter wheat cover crop scenario. Extrapolated to the entire US com belt, the model results suggest that, under the current mix of tillage practices, soils used for corn and/or soybean production will lose 3.2 x 10^6 tons of C per year for the next 100 years. About 21 % of this loss will be C transported off-site by soil erosion; an unknown fraction of this C will be released to the atmosphere. For the base trend and increased no-till trend, these soils are projected to lose 2.2 x 10^6 t-C yr^{-1} and 1.0 X 10^6 t-C yr^{-1}, respectively. Under the increased no-till plus cover crop scenario, these soils become a small sink of 0.1 x 10^6 t-C yr^{-1}. Thus, a shift from current tillage practices to widespread use of no-till plus winter cover could conserve and sequester a total of 3.3 x 10^6 t-C yr^{-1} in the soil for the next 100 years.

Phillips, Donald L., Jeffrey J. Lee and Rusty F. Dodson. 1996. Sensitivity of the US corn belt to climate change and elevated CO_2: I. Corn and soybean yields. Agricultural Systems 52:481-502.

Climate models indicate that increasing atmospheric concentrations of CO_2 and other greenhouse gases could alter climate globally. The EPIC (Erosion Productivity Impact Calculator) model was used to examine the sensitivity of corn and soybean yields over the US corn belt to changes in temperature, precipitation, wind, and atmospheric CO_2 concentration. A statistically representative sample of 100 corn and soybean production sites was selected from the 1987 National Resources Inventory (NRI). One--hundred-year simulations were run for each site under 36 different climate/CO_2 scenarios. The results were area weighted according to the NRI area expansion factors to produce a regionally aggregated estimate of yields. EPIC did an excellent job of reproducing current regional mean expected yields under the baseline scenario. There were 3% decreases in both corn and soybean yields in response to a 2°C temperature increase at baseline precipitation levels, with larger and smaller temperature effects under drier and wetter conditions, respectively. Crop yields increased and decreased in response to increases and decreases of 10% or 20% precipitation. A 10% precipitation increase roughly balanced the negative effect of the 2°C temperature increase. Whether the precipitation changes resulted from altered precipitation event frequency or amount per event had little effect on mean crop yields; however interannual yield variability was higher when precipitation decreases were due to frequency rather than intensity. The opposite was true, though to a lesser extent, for precipitation increases. Potential evapotranspiration responded linearly to changes in mean mind speed, leading to modest changes of 1-3 days of water stress per growing season, yield increases of up to 2% for decreased wind, and yield decreases of up to 6%.for increased wind. Elevated CO_2 concentrations of'625 ppmv gave the greatest yield increases, + 17% for corn and + 27% for soybean at baseline temperature and precipitation levels. The relative CO_2 effect was larger under drier conditions.

Phillips, D.L., D. White and C.B. Johnson. 1993. Implications of climate change scenarios for soil erosion potential in the USA. Land Degradation and Rehabilitation 4:61-72.

Atmospheric general circulation models (GCMS) project that increasing atmospheric concentrations of CO_2 and other greenhouse gases may result in global changes in temperature and precipitation over the next 40-100 years. Equilibrium climate scenarios from four GCMs run under doubled CO_2 conditions were examined for their effect on the climatic potential for sheet and rill erosion in the conterminous USA. Changes in the mean annual rainfall factor (*R*) in the Universal Soil Loss Equation (USLE) were calculated for each cropland, pastureland and rangeland sample point in the 1987 National Resources Inventory. Projected annual precipitation changes were assumed to be from differences in either storm frequency or storm intensity. With all other USLE factors held constant these changes in *R* translated to changes in the sheet and rill erosion national average of +2 to +16 per cent in croplands, -2 to + 10 per cent in pasturelands and -5 to +22 per cent in rangelands under the eight scenarios. Land with erosion rates above the soil loss tolerance (7) level and land classified as highly erodible (erodibility index >8) also increased slightly. The results varied from model to model, region to region and depended on the assumption of frequency *versus* intensity changes. These results show the range of sensitivity of soil erosion potential by water under projected climate change scenarios. However, actual changes in soil erosion could be mitigated by alterations in cropping patterns and other management practices, or possibly by increased crop growth and residue production under higher atmospheric CO_2 concentrations.